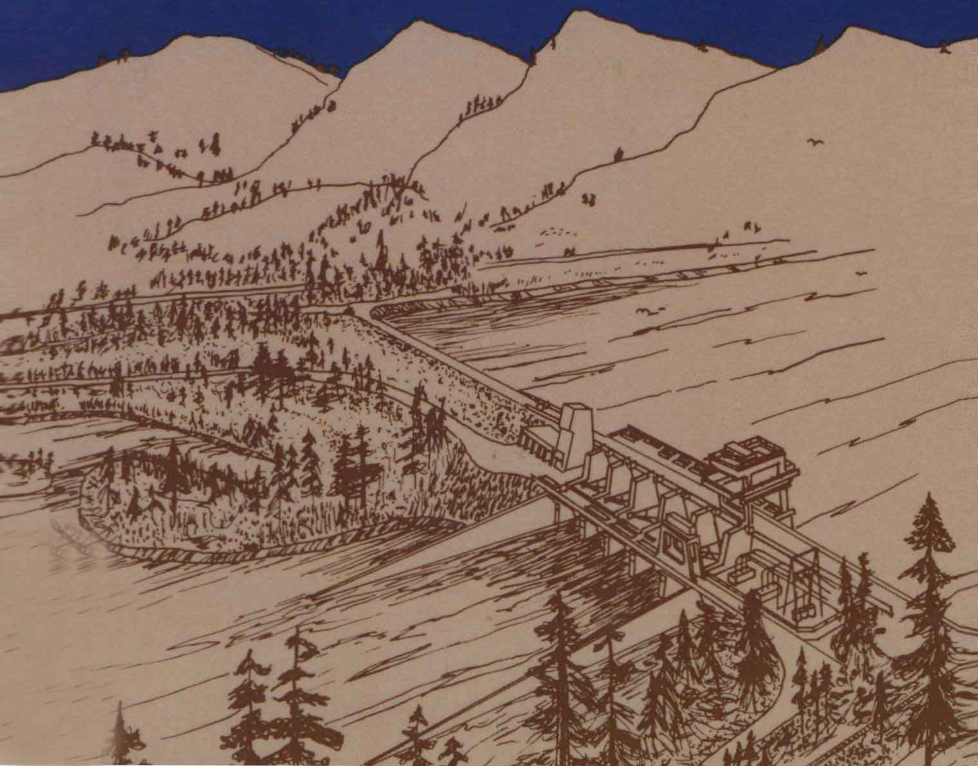
Innovative Powerhouse Designs

Edited by Glenn R. Meloy



Innovative Powerhouse Designs

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FOREWORD

Since 1978, interest in small scale hydroelectric projects in the U.S. has jumped to a new high. Both new sites and modification of existing dams have received scrutiny by both private interests and Governmental agencies. New hydro sites and retrofit projects both face interesting challenges in meeting construction problems, environmental impacts, and flood protection problems.

The three papers presented in this publication describe innovative solutions to the problems facing modern hydroelectric project designs. Two of the papers outline schemes to add power facilities to existing dams by using barge mounted hydro units. The paper by Mr. Calvert focuses on a hydroelectric barge that is floated in and out of a spillway opening on a seasonal basis. The paper by Mr. Broome outlines a method using an intake barge, siphon penstock, and turbine-generator barge at an existing low-head dam. The paper by Mr. Raisanen describes a powerhouse located at a new re-regulating dam that is combined with the spillway monoliths.

Each of the papers presented received several independent peer reviews. All papers are eligible for written discussion in the Journal of Energy Engineering and all papers are eligible for ASCE awards.

The Energy Division is pleased to sponsor this session on Innovative Powerhouse Design. These papers should provoke thought and discussion on other methods that might be used to provide hydro generation in sites that have been considered uneconomical in the past.

The Hydroelectric Barge

James D. Calvert, Jr., F. ASCE*

The nation's inland waterway system includes many low head locks and dams, with undeveloped hydropower potential estimated in excess of 1,100 MW. For most of these dams, hydro development by conventional, traditional means is technically difficult, prohibitively expensive and environmentally objectional. To overcome these problems, a new concept in hydropower generation, the Hydroelectric Barge, has been developed. It is a specially manufactured vessel containing hydro units; once towed to the dam site, it is floated in and out of spillway openings on a seasonal basis for power production. The Hydroelectric Barge's size and power capacity depend on the geometry of the spillway opening, hydraulic head and river flow available. During non-flood periods, the barge is submerged and anchored into the spillway opening for sustained power production. Immediately prior to floods, the barge is quickly disconnected, refloated and removed to a nearby mooring point so that the spillways are clear for flood discharge. The important advantages of the Hydroelectric Barge are low cost, staged installation and minimal environmental impact. Initial installation of the barge is currently scheduled for locks and dams on the Upper Mississippi River.

Introduction

The development of hydroelectric power at existing locks and dams is an important goal in reducing dependence on foreign energy sources. More than 1,100 MW of hydropower potential remains for the entire Mississippi River navigation system. Unfortunately, much of this potential is difficult and costly to develop due to low hydraulic head, flood protection provisions, major in-river construction problems and significant environmental impacts.

On the Upper Mississippi River between St. Louis, Missouri, and St. Paul, Minnesota, about 400 MW of hydropower potential awaits development at 19 existing locks and dams. This paper describes work underway to implement an innovative new concept in hydropower, termed the Hydroelectric Barge (HEB), with initial application at Lock and Dam No. 8 near Genoa, Wisconsin, on the Upper Mississippi River. The location of Lock and Dam No. 8, shown on Figure 1, is about 168 river miles (270 km) downstream of St. Paul-Minneapolis. This facility was built in 1936 as a part of the Mississippi River Nine Foot Channel Navigation Project and is operated and maintained by the U.S. Army Corps of Engineers, St. Paul District.

An aerial view of Lock and Dam No. 8 is shown on Figure 2. The facility consists of a main lock 110 feet (33.5 m) wide, 600 feet (183 m) long, and with a

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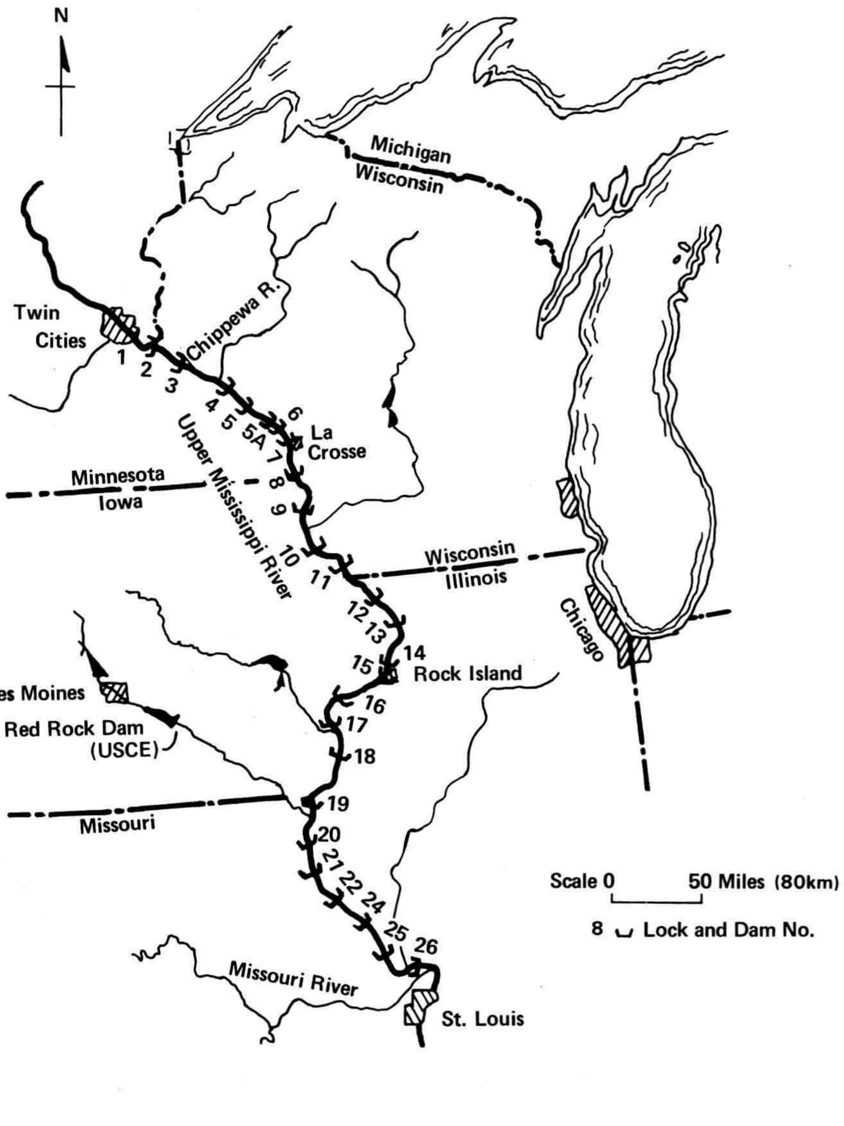


Figure 1. Location Map

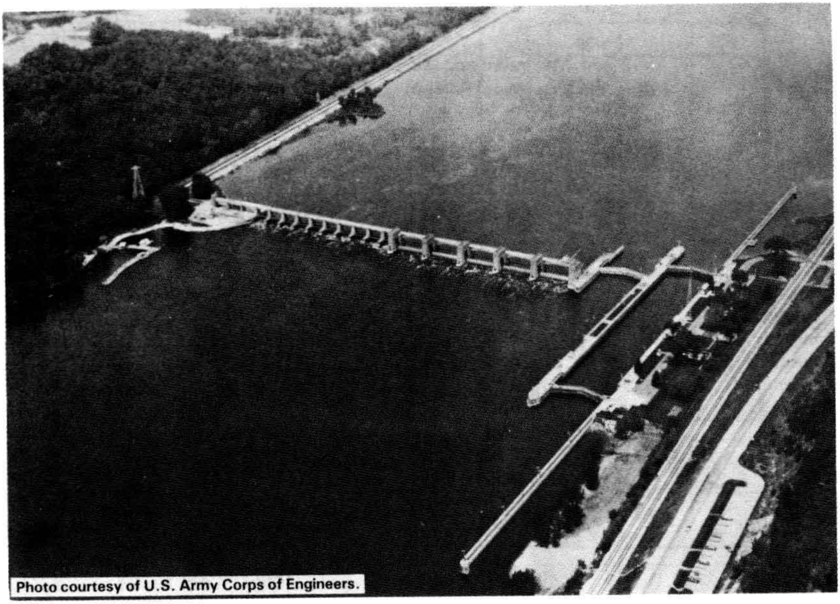


Figure 2. Aerial View Lock and Dam No. 8

maximum lift of 11 feet (3.35 m). The movable dam section extends westward from the lock and consists of five steel roller gates measuring 20 feet (6.1 m) by 80 feet (24.4 m) and ten tainter gates measuring 15 feet (4.6 m) by 35 feet (10.7 m).

At the outset, studies of hydropower potential at Lock and Dam No. 8 involved conventional methods of development with a 10 MW powerhouse operating under a rated head of 9 feet (2.74 m) and located at the opposite end of the dam from the navigation locks. However, these studies showed that this power would not be cost effective, and other means of developing the potential were investigated.

As a result, the HEB concept was developed specifically for application at Lock and Dam No. 8 and similar dams on the Upper Mississippi. It consists of a specially manufactured vessel containing hydro units and is floated in and out of the roller gate spillway openings on a seasonal basis for power production. A U.S. Patent has been obtained for the concept.

Hydrology

The Mississippi River basin above Lock and Dam No. 8 drains 64,770 square miles (168,000 sq km). The average annual flow based on 43 years of U.S. Geological Survey records is estimated to be 32,400 cfs (918.2 cms). During the cold winter months, flows are in the range of 10,000 cfs (283 cms) to 15,000 cfs (425.1 cms). Low flows are significantly enhanced by upstream storage. Flood flows occur in April and March following the spring thaw with the maximum of

TABLE 1

Mean, Maximum and Minimum Monthly Flows for the Mississippi River at Lock and Dam No. 8[1]

Month	Flow at Lock and Dam No. 8 (cfs)		
	Mean	Maximum	Minimum
October	23,070	56,310	9,480
November	23,980	51,770	10,430
December	18,390	37,890	9,130
January	16,550	33,240	7,360
February	16,820	42,740	9,540
March	33,930	90,920	12,670
April	69,530	158,250	27,930
May	55,900	114,450	17,510
June	46,110	95,010	15,750
July	35,830	76,770	12,200
August	23,910	66,470	9,920
September	24,830	54,420	10,230
Annual	32,400	48,250	16,710

Note:
1. Based on flow records of the Mississippi River at McGregor (USGS No. 05389500)
2. 1 cfs = 0.0283 cms

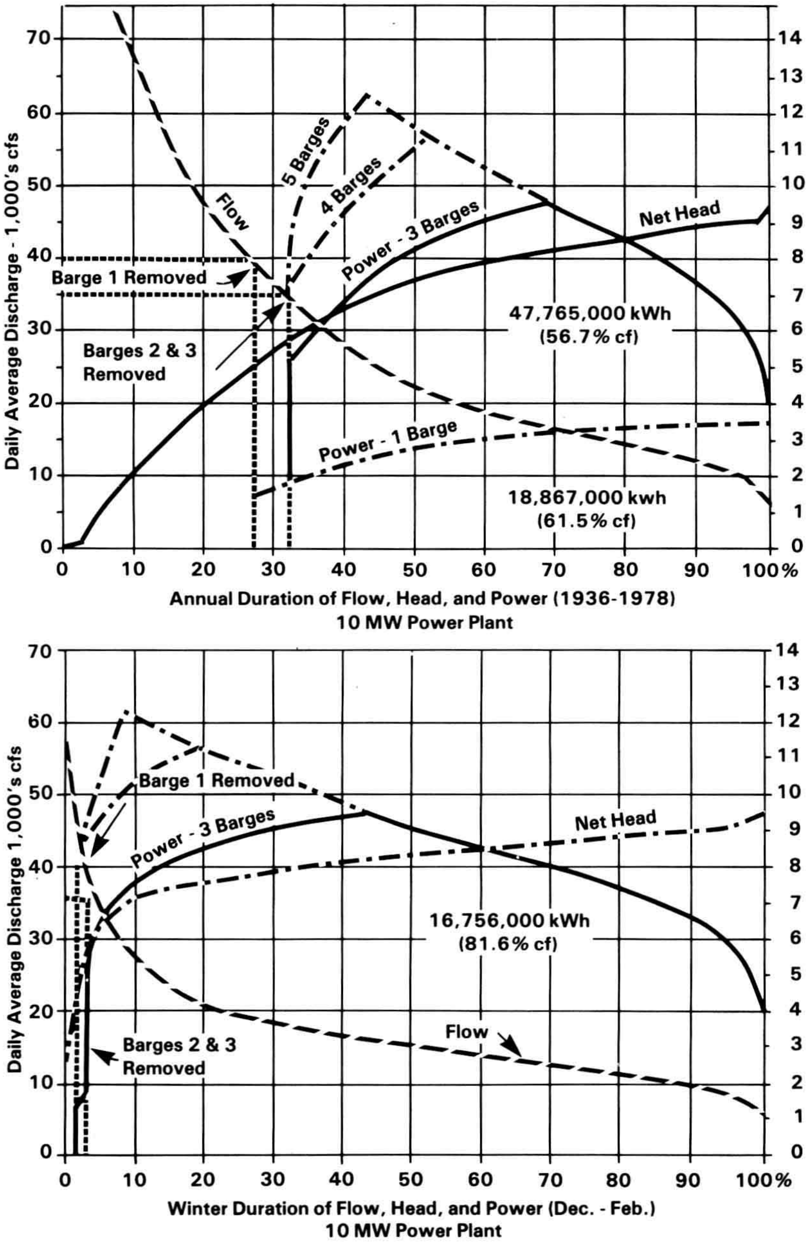
record, 274,000 cfs (7,765 cms), occurring in April 1965. Table 1 depicts the range of monthly flows at this location. Duration of daily average flow values over the period of record for the entire average year and for the four month winter period are shown on Figure 3.

Average annual temperature at this location is 46.4°F (8°C) with average monthly extremes of 16.6°F (-8.5°C) in January to 72.8°F (22.7°C) in July. Average annual precipitation at nearby LaCrosse, Wisconsin, is 30.9 inches (78.5 cm). On average, about 48 inches (122 cm) of snow falls each winter.

Power and Energy

The fundamental factor influencing power and energy available at Lock and Dam No. 8 is the hydraulic head available throughout the range of river flows. At the normal low flows, gross head available is about 10.0 feet (3.05 m); as flows increase, gross head decreases to about 6.7 feet (2 m) at average flow and 0.28 feet (0.09 m) for the flood of record. Duration of net head curves are shown on Figure 3.

Basically, a hydro plant at Lock and Dam No. 8 would be a "run-of-river" installation since it is not possible to re-regulate flows and water levels to any significant degree. The proposed installation would consist of three HEBs with each containing five hydroelectric units of 700 kW each operating under a net



Note: 1 ft = 0.305 m., 1 cfs = 0.0283 cms

Figure 3. Duration of Flow, Head and Power

TABLE 2

Performance of Allis-Chalmers Hydroelectric Barge Tube Turbine

	Turbine			Generator	Overall
Net Head (ft)	Output (kW)	Discharge (cfs)	Efficiency (%)	Output (kW)	Efficiency (%)
9.0	762	1,115	89.6	704	82.8
8.5	722	1,107	90.5	667	83.7
7.0	542	1,031	88.6	500	81.8
5.0	288	944	72.0	200	50.0

head of 9.15 feet (2.79 m). Thus, each vessel has a rated capacity of 3,500 kW with a total installed capacity of 10,000 kW. As river flows increase and head available decreases, power output declines until at around a flow of 35,000 cfs (992 cms), when output is 5,000 kW.

The performance characteristics of the proposed hydroelectric units have been developed by the Allis Chalmers Company and are shown in Table 2. The maximum, "water-to-wire" efficiency of these units is 83.7 percent at 8.5 feet (2.6 m) of head.

Duration of power curves for the average year and for the four month winter period are shown in Figure 3. It will be noted that for 30 percent of the time the plant is inoperative due to floods and insufficient head. However, during the peak electrical load period in the winter, power output holds up quite well, and the entire plant capacity is thereby considered firm power.

Average annual net energy from the three HEBs after deducting for certain losses will be 47,500,000 kWh. This is about 9 percent less than a conventional hydro plant at Dam No. 8 would produce as it would operate for a slightly longer period of time at high river flows when, alternatively, the HEBs have been removed.

Project Operation

The HEBs proposed at Lock and Dam No. 8 will be operated as closely as possible in accordance with present operating procedures of the Corps of Engineers.

Critical to the success of the HEB concept is the timely and fast removal of the vessels from the roller gate spillways prior to arrival of floods. On a large and well regulated river such as the Upper Mississippi, substantial warning time is available for both spring floods from snowmelt and from storm rainfall. Further, quite reliable flood prediction is available from the Corps of Engineers and the National Weather Service.

Studies of HEB placement and removal have determined that an inflow estimate of 35,000 to 45,000 cfs (992 to 1,275 cms) is the limiting flow at which

TABLE 3

Estimated Times of Operations Required for Hydroelectric Barge Removal

	Step	Time (Mins)
1.	Mobilization	30
2.	Preparation for Removal	
	Shut Down Units	5
	Close Roller Gate	10
	Disconnect Seals	5
3.	Ballast, Cables	
	Commence Ballast Pumping	45
	Connect Shore Cables to Capstans	30
	Disconnect Power Cables and Start Diesel	10
4.	Remove	
	Release Downstream (150 ft ±)	15
5.	Transit	
	Pull to Lock Wall	20
6.	Dock	
	Move Upstream in Auxiliary Lock (150 ft ±)	15
	Dock	15
	REMOVAL TOTAL TIME	3 hrs ±

the ability of Lock and Dam No. 8 to maintain navigable waters or to pass target flows will not be adversely affected. Hence, target river flows for removal or replacement of the HEBs will be in this range.

Detailed hydrologic studies of floods and travel times indicate that a period of from five to ten days is available between flood producing events and the arrival of the target flow rate for removal of the barges. Careful coordination with the Corps of Engineers and the National Weather Service will be required in planning for the removal and replacement of the HEBs. On average, the barges will need to be cycled in and out about one and a half times per year.

An estimate of the time required for removal of each barge from the roller gate spillways is about three hours, as shown in Table 3. All three barges can be removed within an eight hour working day. During the removal period a river tug will be available to assist with the vessels in addition to the cable-winch system.

Careful manipulation and gate changes are required throughout the removal and replacement cycle in order to maintain proper river flow rates through the dam. Figure 4 shows the vessel in the transport mode. Figure 5 is a view of a HEB model in-place in a roller gate bay.

Project Description

The concrete structures at Lock and Dam No. 8 are supported on timber pilings, driven into sand and gravel with steel sheet piling cutoff walls. The roller gate bays which are to receive the HEB consist of concrete piers 15 feet (4.57 m) wide with an enlarged base to transfer roller gate loads to the timber piling beneath. In the 80 foot (24.4 m) span between the piers a concrete spillway apron and upstream ogee section completes the structure, but takes only water

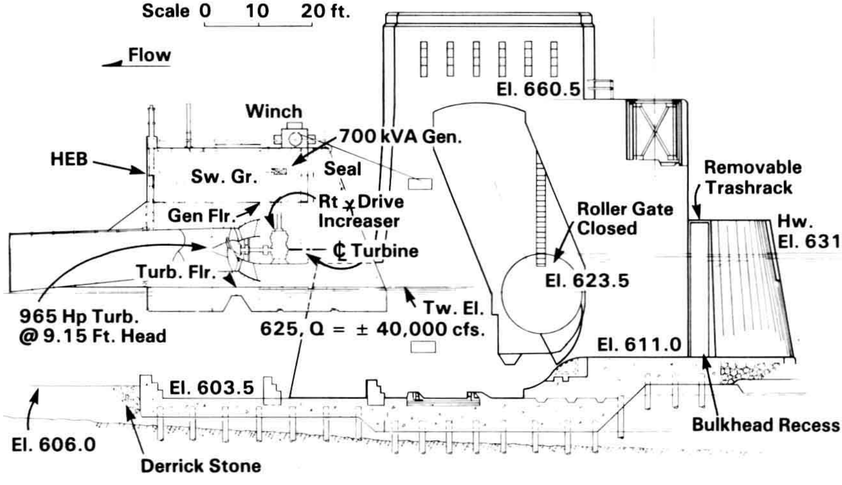


Figure 4. Cross Sectional View - Hydroelectric Barge and Roller Gate Bay - Transport Mode

loads imposed directly on it. These loads are also transmitted to the foundation through timber piling. The steel roller gate is 15 feet (4.57 m) in diameter but with a "beak" projection of 5 feet (1.52 m) on one side to give the 20 foot (6.1 m) closure height. The roller gate is raised and lowered by means of electric hoists atop the piers and travels on a cogged track within a pier recess. Certain details of the roller gate bay can be seen in the cross-section on Figure 4.

The design of the HEB is influenced by two major factors: 1) the size and configuration of hydropower water passages and equipment space as required to maximize power production, and 2) the geometry, configuration and structural requirements as dictated by the receiving spillway and resultant water loads and transfer points when the barge is in place.

At Lock and Dam No. 8, the water discharge capacity for power is based on the maximum amount which can flow through the forebay approach to the roller gate at a velocity not to exceed 3.5 feet per second (1.07 m/s). Thus, each barge can receive up to 5,575 cfs (158 cms) of water for power purposes.

Turbine Generators - A number of turbine types and configurations were studied, including standardized designs. The selected design is basically a "pit" type installation as shown on Figure 4. Each barge will contain five of these turbines to be supplied by the Allis Chalmers Company. They will be of the axial flow, horizontal shaft type directly connected to a vertical induction generator through a right angle, double reduction transmission, speed increaser. The turbine will be unregulated, and as such, a fixed, three blade type. Centerline spacing of the units is approximately 16 feet (4.9 m). Starting and stopping of the turbine will be by means of a special draft tube control gate downstream of the runner. The units will be capable of sustained operation under runaway speed conditions following load rejection or other malfunctions. This will ensure uninterrupted flow past the dam until such time as the problem can be corrected.

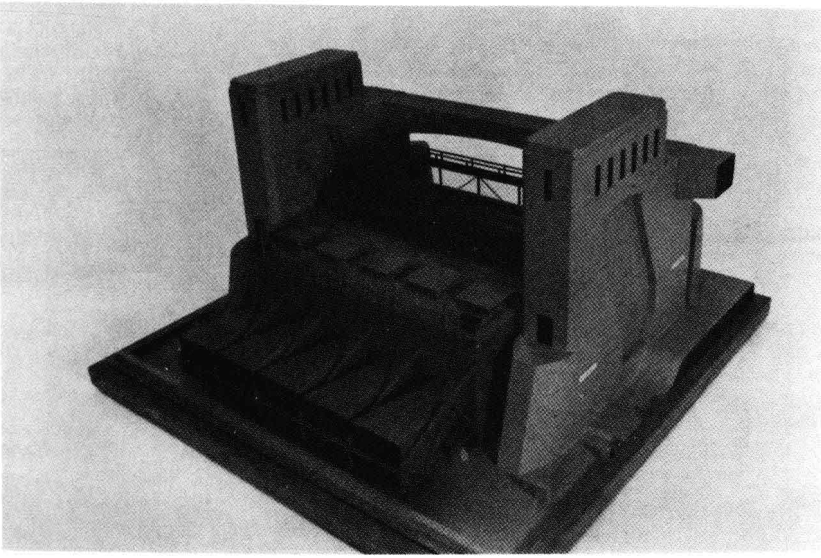


Figure 5. Hydroelectric Barge in Place

Back-up shutdown of the units can be accomplished by closing of the roller gate upstream.

Each generator is a synchronous squirrel cage, induction type, rated 3 phase, 60 hertz, 4160 volts, 750 kVa, vertical shaft. Generator nameplate rating is 700 kW at 1,200 rpm.

Electrical Equipment - Each generator will be connected to a 4,160 volt bus through 250 MVA circuit breakers. Power will flow from the 4,160 volt bus on the barge through power cables across the dam to a 69 kV, 10,000 kVa transformer on the shore which will step-up the voltage for connection to a 69 kV line at that point. An auxillary 480 volt system will be provided on the barge to supply pumps, winches, heaters and lighting. A 110 kW diesel generator will be installed on each barge to provide auxiliary power when the barge is disconnected from the dam.

Miscellaneous Mechanical Equipment - To facilitate movement of the barge under either normal or emergency conditions, a diesel generator, winches and pumps will be on board. The winches, located on the barge deck, are capable of pulling (and holding) the vessel into the gate bays or controlling the withdrawal from the bay. They are also capable of pulling the barge to the auxiliary lock wall for mooring. The pumps on board will transfer water to and from the ballast tanks which control trim and vertical movement and for drainage of sumps. Other mechanical equipment includes a trash rake, generator room hoist and other minor equipment for lube oil and HVAC.

To provide certain debris and ice protection to the HEB and roller gate, a removable trash rack will be inserted in the bulkhead gate slot upstream during

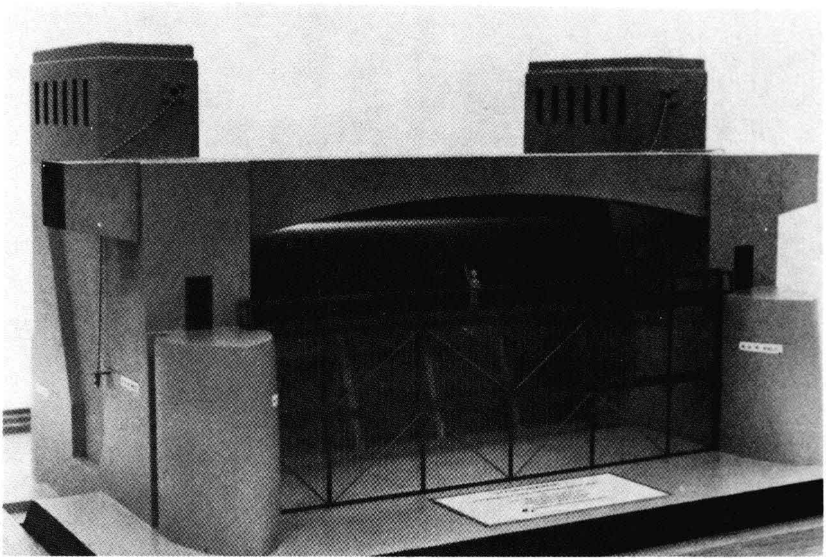


Figure 6. Upstream View Ice and Debris Trashrack in Place

operation. It will be handled by the traveling locomotive crane atop the spillway bridge. Figure 6 shows the trash rack in-place for the operating mode.

Hydroelectric Barge Design - Each HEB will be an all welded, steel vessel 78 feet (23.8 m) long by 39 feet (11.9 m) wide. It will be divided into separate watertight ballast compartments. Each barge, including all equipment on board, will have a dead weight of about 375 tons (340,200 kg). Controlled filling of individual compartments will provide trim for transporting the barge, as well as controlled submergence and refloating. The hull forms a vessel which is transportable similar to a barge but which can also be submerged to act as a water retaining structure in the power generating mode.

The HEB will be fabricated at a facility with water access to the Mississippi River. A river tug boat will then push it to the Lock and Dam No. 8 site. The barge will then be berthed in the area reserved for the uncompleted auxiliary lock.

When river flow conditions are proper for power generation, a tug boat will tie up to the barge and move it into place in front of the roller gate bay. At this point a cable will be attached from each pier to each side of the barge. When the cables are secure, the tug boat will be untied and the barge will be winched into final position with the cables. Timber faced fenders with a sloped leading edge will be provided to guide the barge in the bay. Vertical bumpers will also project from the side of the barge for its full height. The upstream vertical outside surfaces will strike bumper brackets attached to the piers. The bumper will be located to place the HEB in its proper position in front of the closed roller gate. During this operation, flow through adjacent gates will be restricted to reduce turbulence. Figure 4 depicts the HEB moving into position in the roller bay.

At this time, ballast tanks will be filled in a controlled manner to slowly submerge the HEB. After the barge comes to rest on the foundation, additional ballast will be added to provide stability for all operating conditions. With proper ballasting, it will be possible to maintain an adequate safety factor for overturning and uplift for all operating tailwater conditions.

When the roller gate is opened and the headwater pressure is applied to the face of the HEB, the horizontal thrust bearing will come in contact with the specially installed restraint on the piers at Elevation 610.0. The HEB reactions will now be statically determinate with all horizontal forces taken at Elevation 610.0, and all vertical forces taken by the spillway and apron. Support points and loadings are shown in Figure 7.

The top of the ballast compartments at Elevation 610 will act as a stiffened diaphragm to transmit horizontal hydrostatic forces to the pier restraints. In a similar manner, the walls between the turbine bays will act principally as diaphragms to transmit vertical forces to the spillway and apron. The forward bearing surface will also serve as the bottom waterstop in conjunction with seals on the sides.

The ballast tanks will be stiffened with longitudinal trusses at 18 inches (45.8 cm) on center. The top plate and bottom plates of the ballast tanks will be

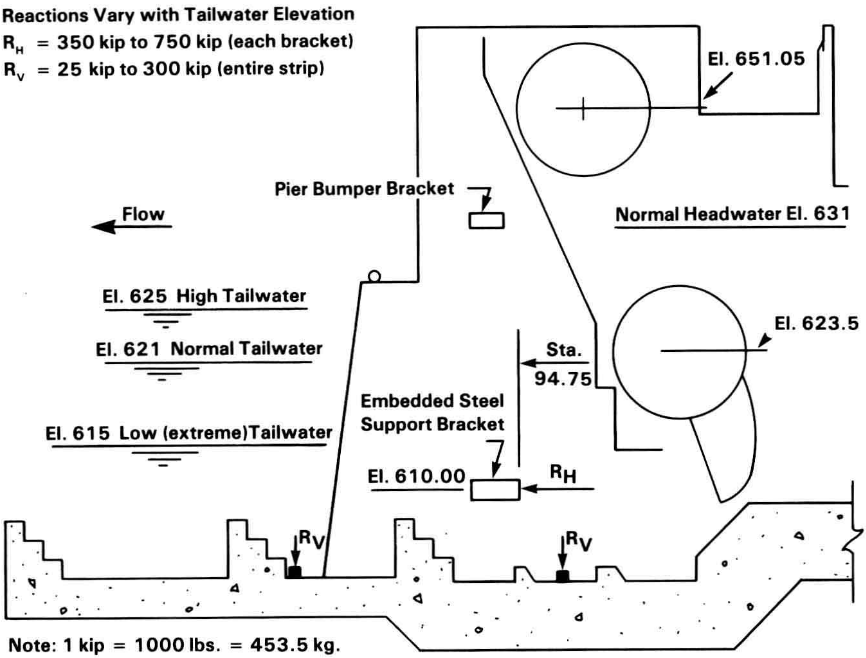


Figure 7. Hydroelectric Barge Load Points

designed as an orthotropic plate structure to incorporate the plate area into the chords of the stiffening trusses. The trusses will frame to the transverse compartment walls, thus forming a very stiff, lightweight structure. Principally the remainder of the structure will be fabricated with 1/4 inch (6.4 mm) plate stiffened as required for hydrostatic forces of other live loads. The vessel will be fabricated from ASTM A-36 steel plates and rolled shapes.

Foundation and Loadings - The concrete foundations of the roller gate bays are supported on timber pilings designed for 30 ton (27,210 kg) bearing capacity under the piers, 20 ton (18,140 kg) under the sill and 15 ton (13,605 kg) under the concrete apron.

When the HEB is in its submerged position and the roller gate is down, the roller gate will be resisting all hydrostatic forces. When the roller gate is raised, the horizontal hydrostatic loads will be transferred from the roller gate to the HEB. In terms of overall stability of the dam it makes very little difference if the roller gate or the barge is the structure that transmits forces to the piers. The hydrostatic head and the span between the piers is the same for either case.

Each of the foundation elements will, however, receive loads from the HEB in a slightly different manner than they do from the roller gates.

When the roller gates are in their closed position, they deliver forces to the pier stem at Elevation 621.9. The HEB support brackets will be at Elevation 610.0 which will greatly decrease the lever arm of the overturning moment on the pier. However, the barge will rest on the lower portion of the foundation slab (Elevation 603.5), so that magnitude of the horizontal reactions will be larger.

The original design condition for the pier foundation piles was based on one bay dewatered and one bay at design headwater on either side of the pier. Loads imposed on these pier pilings by the HEB in place are very similar to those of the original design.

The sill foundation will receive the HEB forward vertical reaction as a line load extending the full distance between piers minus end clearance. This line loading will be located as shown on Figure 7.

The sill foundation was originally designed to accept a steel cofferdam foundation load of 4.2 kips (1,905.1 kg) per foot. The HEB will impose a line load of less than 1.8 kips (816.5 kg) per foot in essentially the same location.

The concrete thickness of the apron foundation slab is 3.5 feet (1.0 m) and is supported by timber piles with a minimum bearing capacity of 15 tons (13,605 kg).

The HEB rear reaction will vary with tailwater elevations, but it will not exceed 300 kips (136,080 kg) across the width of the barge. The foundation slab is lightly reinforced but it does have adequate strength to distribute this load to the piles on either side of the reaction. These piles would then receive a total load of 12 tons (10,884 kg) per pile with the HEB in place, well within their design load of 15 tons (13,605 kg).

Stability and Ballasting - The HEB will be equipped with the necessary pumps, valves, instruments and controls to provide the following performance capabilities:

1. In completed condition, but with a minimum of water ballast, the vessel will:

    a. have positive stability, and

    b. float reasonably close to upright.

2. In condition for transport to and from the dam, as well as when moored away from the dam, the vessel will:

    a. have positive stability, including the effect of free surface of liquids on board,

    b. float upright with ballasting capability to adjust heel or trim,

    c. have a draft no more than the 9 feet (2.7 m) which is the standard on this inland waterway,

    d. have sufficient compartmentation such that accidental flooding of any one compartment would not sink the unit,

    e. be rugged enough to be towed to the site and allow safe passage through the locks, and

    f. be capable of being dry docked for inspection and repair.

3. In initial positioning condition at the dam the vessel will:

    a. have a positive stability including free surface of liquids on board,

    b. float upright, and

    c. be able to clear all obstructions at the entry to the downstream side of the dam (e.g., the dissipator blocks in apron and sill area).

4. During positioning, ballasting and removal the vessel will:

    a. have a positive stability in all interim ballasting conditions,

    b. have positive control of draft, trim and heel between initial positioning condition and fully seated on dam supports and anchors, and

    c. be able to be ballasted down without using the turbine water passage as a ballast compartment. The turbine water passage would be flooded as the HEB descends to its final resting position.

5. In its generating position, the vessel will:

    a. be capable of remaining in place completely unattended through applicable range of river level stages, and

    b. be capable of being deballasted and removed with control of draft, trim, heel and stability.